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The effect of repeated visual motion stimuli on visual dependence and postural control in normal subjects

Marousa Pavlou [a], Catherine Quinn [a], Kate Murray [b], Chrysa Spyridakou [a], Mary Faldon [a], Adolfo M. Bronstein [b,*]

[a] Academic Department of Physiotherapy, School of Biomedical Sciences, Centre for Human and Aerospace Physiology, Kings College London, London SE1 1UL, United Kingdom
[b] Neuro-Otology Unit, Division of Neuroscience & Mental Health, Imperial College London, Charing Cross Hospital, Fulham Palace Road, London W6 8RF, United Kingdom

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ABSTRACT

Patients with vestibular dysfunction, migraine and/or anxiety may experience visual vertigo (VV), whereby symptoms are provoked by disorienting visual environments (e.g. supermarkets). Patients with VV over rely on vision for balance (i.e. visually dependent). Visual vertigo significantly improves when vestibular rehabilitation incorporates exposure to optokinetic stimulation (OKS). However, whether OKS exposure induces a reduction in visual dependency is unknown. This study investigated this issue by measuring visual dependency before and after repeated OKS exposure. Twenty-six healthy subjects (10 males; mean age 29.8 years, range 20–42 years) were randomly allocated into an OKS group who underwent graded OKS exposure for five consecutive days, or a no intervention control group. Assessment included the 'Rod and Frame' and 'Rod and Disc' tests where subjects set the subjective visual vertical in darkness, facing a tilted luminous frame or luminous rotating disc, respectively. Postural sway measures were obtained with eyes open, closed and facing the rotating disc. Results showed significant reductions in subjective vertical tilt with the frame and rotating disc for the OKS group only ($p \leq 0.01$). Total sway path and mean deviation induced by the rotating stimulus decreased significantly only for the OKS group ($p < 0.01$), as did the Kinetic Quotient (disc rotation/eyes open sway path ratio; $p = 0.04$). The Romberg Quotient (eyes closed/eyes open ratio) showed no change. Findings suggest visual dependency, both at a perceptual and a postural level, can be reduced with short-term graded OKS exposure in healthy subjects. This has important implications for treatment of patients with VV and balance disorders.

1. Introduction

Patients with a vestibular disorder may report discomfort, postural destabilization, and symptom exacerbation in disorientating visual environments (e.g. supermarket aisles). These symptoms, commonly referred to as visual vertigo (VV) [1], space and motion discomfort [2], or visual vestibular mismatch [3], may include dizziness, light headedness, unsteadiness and disorientation but usually not 'true' rotational vertigo.

It has been suggested that VV, which results from over reliance on visual cues for perception and postural control (i.e. visual dependence), limits vestibular compensation, especially in situations causing visual–vestibular conflict [1,4]. Findings demonstrating a stronger influence of disorienting visual stimuli (tilted or rotating visual surroundings) on verticality perception and postural stability in patients with vestibular dysfunction and VV compared to those without support this view [1,4].

Guerraz et al. [4] recommended patients with VV would benefit from treatment promoting desensitisation and increased visual motion tolerance, through exposure to optokinetic stimulation (OKS). A study testing this hypothesis showed customized vestibular rehabilitation becomes more beneficial when incorporating OKS exposure via whole-body or visual environment rotators—improving dizziness, postural instability, and particularly VV symptoms in patients with chronic peripheral vestibular dysfunction [5]. However, visual dependency was not measured [5] and the exact recovery mechanism remains unidentified. We hypothesize visuo-vestibular rehabilitation improves symptoms in patients with VV via plastic, adaptive changes in visual dependency magnitude. However, whether it is plastic is unknown. This study investigated this issue by measuring visual dependency, at both a perceptual and a postural level, before and after repeated OKS exposure, in healthy subjects.

2. Materials and methods

Subjects were randomly assigned to a control (no intervention) or OKS group (OKS training). The OKS group attended 1-h daily sessions for five consecutive days with a therapist. Both groups completed all tests on days 1 and 5 and were asked to

* Corresponding author. Tel.: +44 0208 846 7523; fax: +44 0 208 846 7577.
E-mail address: a.bronstein@imperial.ac.uk (A.M. Bronstein).

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refrain from taking alcohol 24 h prior to testing. Local ethics committee approval was obtained.

2.1. Experimental apparatus and techniques

The Rod and Frame (Fig. 1A) and Rod and Disc (Fig. 1B) apparatus provided the static or dynamic visual disturbance, respectively, for SVV and/or postural sway recordings [4].

2.1.1. Subjective visual vertical (SVV)

Subjects sat upright 80 cm, eye leveled, from the frame or disc. A chin rest secured head position. Before each trial, subjects closed their eyes and the rod was tilted ±40°, in counterbalanced order, randomized between subjects for each test condition. Subjects then adjusted it to their perceived gravitational vertical in their own time. Rod settings in darkness (no frame or disc rotation) were completed first, followed by static tilted frame (±28°) or rotating disc (±30°/s) settings. Ten trials were completed for rod only and frame conditions and four for each rotating disc condition as it is quite disorientating and trial number was kept to a minimum.

A potentiometer recorded SVV values, taken as angular deviations from true gravitational vertical (0°) measured in degrees. Tilt of the rod's top to the subject's right or left was indicated as a positive or negative value, respectively. Each subject's average SVV value in darkness or with the disc stationary served as a baseline for values obtained with frame tilt and rotating disc, respectively.

2.1.2. Postural sway

Subjects wore a harness attached to an overhead beam and stood barefoot on an 18 cm high force platform (AMTI, USA) with arms hanging at their sides. Foot positioning was based on footprints symmetrically drawn on the force platform at a 30° angle with heels 2.5 cm apart. Postural sway was recorded in the lateral and antero-posterior direction using the force platform for centre of foot pressure (COP). All signals were digitally sampled at 50 Hz.

Postural sway was recorded with (i) eyes open (EO): subjects fixated for 45 s on a fluorescent dot at the stationary disc's centre in a lighted room; (ii) eyes closed (EC) for 45 s; and (iii) disc rotation: subjects fixated on the fluorescent dot in a darkened room; after a 15 s baseline recording, the disc rotated at a constant velocity of ±30°/s, for 45 s. Disc inertia meant a 2–3 s acceleration period occurred before reaching steady state velocity. EO and EC conditions were completed in counterbalanced order, prior to rotating disc conditions (with a counterbalanced order of clockwise and counterclockwise rotations).

Subjects completed SVV tests first to familiarize themselves with the dynamic visual stimuli; then rested for 15 min before postural sway tasks to recover from any symptoms provoked. Testing lasted approximately 45 min, including the rest period.

Two sway parameters were calculated from COP recordings: (A) average postural deviation during disc rotation calculated as mean COP change in the lateral direction (disc rotation plane) during 45 s of rotation relative to the preceding baseline period; (B) total sway path, the path length described by the COP which combines lateral and antero-posterior sway and is the sum of absolute distances from one point to the next during the recording period. The Romberg [6] (ratio between sway path with EC/EO) and Kinetic [4] (ratio between sway path during disc rotation/EO) Quotients, which assess the stabilizing and destabilizing effect of vision in postural control, respectively, were also calculated.

2.2. Subjects

Twenty-six healthy subjects (control group: 5 males; mean age 31.9 years, range 24–42 years; OKS group: 5 males; mean age 27.7 years, range 20–40 years) without evidence of vestibular or neurological disease, acute orthopedic injury, or migraine history, participated after providing informed consent and completing a medical screening. Subjects were recruited via email to Imperial College London staff and students. All subjects were asked to continue their daily, including medical and academic, activities as normal between the pre-/post-test period.

Subjects completed a short form regarding sports participation, sports activities and weekly exercise duration. Twenty-two subjects (84%) participated in sport and 16 (72%) participated in more than one sport regularly. The most common activities were cycling, running, rock climbing, and swimming. Average weekly exercise duration was 4.27 (SD 3.27 h, range 0–9 h) and 3.59 h (SD 2.75 h, range 0–10.5 h) for the control and OKS groups, respectively.

Subjects who answered "yes" (control group: $n = 2$ females; OKS group: $n = 4$ females) to experiencing motion sickness either in the past or currently, completed the Short-form Motion Sickness Questionnaire [7] which yields a composite percentile rank between 0% and 100% based on nausea and vomiting susceptibility during various types of motion (e.g. car travel) prior to age 12 and over the last 10 years. Average percentile rank was 72.4% (SD 39.7%) and 57.4% (SD 30.4%) for the control and OKS groups, respectively. Subjects without motion sickness were assigned a "0" score for statistical analysis.

2.3. OKS training

2.3.1. Optokinetic disc (equipment as above; Fig. 2A)

Subjects focused on the disc's centre, eye leveled, while it rotated at discrete constant velocities between ±10°/s and 60°/s according to individual tolerance.

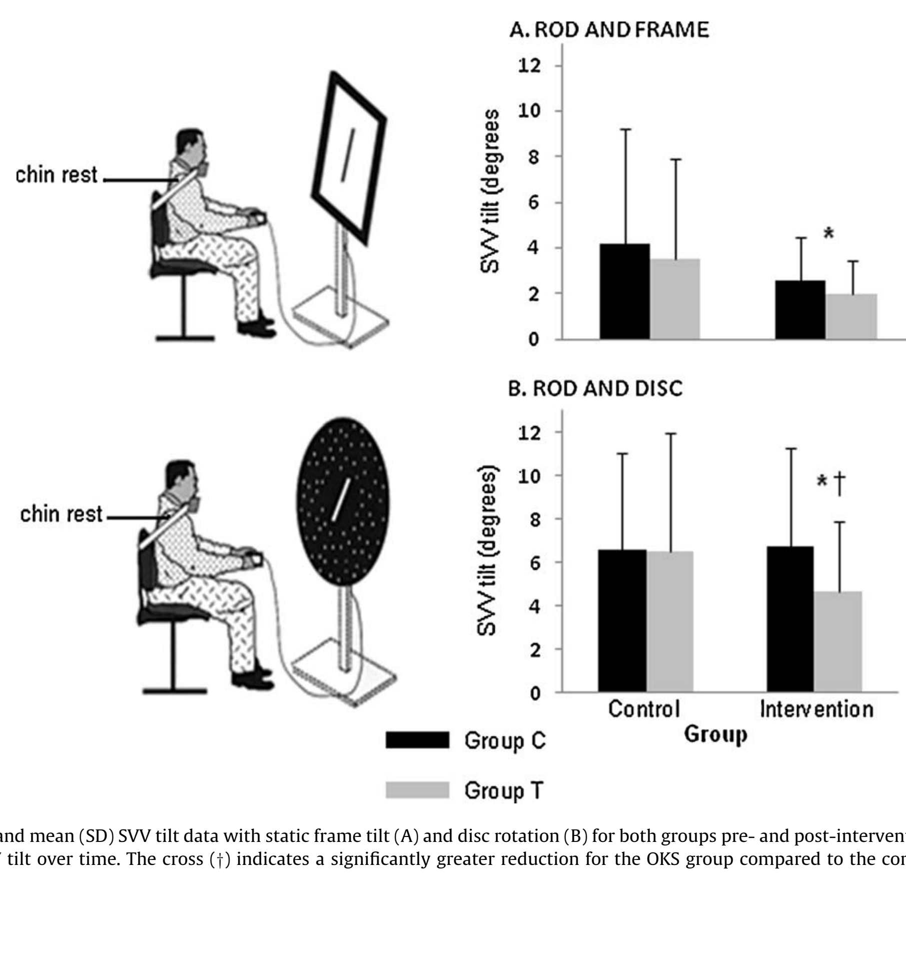

Fig. 1. Experimental set-up and mean (SD) SVV tilt data with static frame tilt (A) and disc rotation (B) for both groups pre- and post-intervention. The asterisk (*) indicates a significant reduction in SVV tilt over time. The cross (†) indicates a significantly greater reduction for the OKS group compared to the control group.

2.3.2. Optokinetic drum (Fig. 2B)

Subjects sat inside a full-field black and white striped optokinetic drum (radius 0.76 m) on a chair fitted with padded arm, foot and headrests. While the drum rotated horizontally at discrete constant velocities between ±10°/s and 90°/s, subjects were instructed to look ahead and avoid following the stripes with eyes movements ("stare") as this may provoke an unacceptable level of symptoms, particularly nausea. Subjects were constantly reminded to look at the stimulus. Initially the head was stationary but progressively sagittal and horizontal head movements were introduced as tolerated.

Disc and drum inertia meant a 2–3 s acceleration period occurred before reaching steady state velocity. Thus the waveform of the stimuli is best described as velocity trapezoids.

2.3.3. Eye-Trek (Fig. 2C)

A head-mounted display (Eye-Trek FMD-200, Olympus Optical Co. Ltd) with two 0.55-inch LCD panels for image projection. The combined visual angle was 30° horizontally and 22.7° vertically. The goggles were connected to a DVD player, through which a moving tunnel or boat scene (Fig. 3A–C) was projected. Both visual stimuli simulated linear forwards progression and simultaneous roll oscillations of the subject. The forwards linear component appears subjectively fast, as it takes 3 s for a feature near the middle of the screen (where it is first seen to move) to reach the screen edge. The roll motion components were: tunnel scene, amplitude ±720°, frequency 0.03 and 0.06 Hz; boat scene: amplitude ±40°, frequency 0.25 and 0.5 Hz. Subjects were instructed to focus on the centre of the moving scene.

Eye-Trek and optokinetic disc exercises were initially practiced standing on a firm surface without head movements. Progressively, subjects stood on compliant foam cushion and/or practiced sagittal and horizontal head movements as tolerated.

At each session, the number of exercises practiced increased. Each exercise lasted 2 min, followed by a minute break, and was stopped if a subject felt unable to continue due to nausea/dizziness or when symptoms verbally graded at 1 min were reported as moderate or severe. No exercises were practiced until symptoms subsided to nil or mild. If no symptoms were induced, OKS velocity increased in discrete 10°/s increments and/or the exercise was progressed to the next level. All subjects progressed.

2.4. Analysis

SPSS (SPSS Inc., Chicago, USA) was used for statistical analysis. Data are presented as mean ± SD. Between-group differences for all data were determined using one-way ANCOVA with a forward selection strategy for inclusion of covariates (age, motion sickness, weekly exercise duration) and a fixed factor (gender) one at a time. Only the final model is reported; only significant covariate and fixed factor effects are reported ($p < 0.05$). Within-group differences for all data pre (day 1) and post (day 5) intervention were analyzed using paired sample t-tests.

3. Results

No significant between-group differences were noted for baseline SVV and postural sway data. All OKS group subjects tolerated OKS exposure and none dropped out of the study.

As no differences were noted between clockwise and counter-clockwise visual stimuli for SVV settings or postural data, results were normalized by reversing the polarity of values obtained during counterclockwise stimuli, and then combined to obtain average SVV tilt.

3.1. Subjective visual vertical

SVV deviations of the rod alone were close to gravitational vertical for both groups (control: pre 0.25° SD 0.84°, post 0.45° SD 0.92°; OKS: pre −0.16° SD1.20°, post 0.31° SD1.09°); no significant main effects or interactions were observed. During visual disturbances, SVV deviated in the frame tilt or disc rotation direction. A significant within-group effect was noted for both static frame and rotating disc conditions *only* for the OKS group (frame: $t = 2.95$; df = 12; $p = 0.01$; disc: $t = 3.41$; df = 12; $p < 0.01$) (Fig. 1A–B). For the OKS group, 10 and 12/13 subjects showed a reduced static and dynamic SVV tilt response, respectively. A significant between-group difference in dynamic SVV tilt change ($F_{(1, 23)} = 6.81$; $p = 0.02$) was noted with a 31% decrease for the OKS group compared to a 1% change for the control group (Fig. 1B).

A significant effect of motion sickness ($F_{(1, 23)} = 4.54$; $p = 0.04$) on dynamic SVV tilt change during disc rotation was noted, where higher motion sickness percentile scores were associated with greater change. No significant differences were noted between subjects with/without motion sickness and baseline SVV tilt data.

3.2. Postural sway

Postural disc effect: disc rotation induced postural sway in the stimulus direction. Average deviation showed a significant within-group effect only for the OKS group ($t = 3.21$; df = 12; $p < 0.01$; 10/13 subjects) whose average deviation decreased by 70% compared to 41% for the control group (Table 1). No significant between-group differences were noted (Table 1).

Total sway path data with the rotating disc showed a significant within-group effect only for the OKS group ($t = 3.58$; df = 12; $p < 0.01$; 11/13 subjects), with an overall 50% reduction compared to 22% for the control group (Table 2). No significant between-group differences were noted. No significant between- or within-group differences were observed for EO or EC (Table 2).

The *Romberg Quotient* showed no significant between- or within-group effects (Table 1). In contrast, the *Kinetic Quotient* showed a significant within-group effect only for the OKS group ($t = 2.32$; df = 12; $p = 0.04$) (Table 1) but no significant between-group differences. Quotient mean scores for both groups were >1 indicating greater sway with EC, and a destabilizing effect of the disc on postural sway (Table 1).

4. Discussion

This study investigated whether repeated OKS exposure can modify perceptual and postural visual dependency measures. Static and dynamic SVV deviation decreased significantly only for the OKS group with a significant between-group difference for dynamic SVV tilt. Postural sway measures with the rotating disc reduced for both groups but were statistically significant only for the OKS group. Age, gender, and weekly exercise duration did not affect outcome. A significant interaction was noted though between motion sickness and dynamic SVV tilt change with greater change in subjects with higher motion sickness scores. The following discussion is separated into (a) perceptual responses, (b) postural sway responses, and (c) clinical implications.

Table 1
Comparison of mean (SD) COP postural scores in both groups at the pre- and post-intervention assessments.

	Group C		Group OKS	
	Pre	Post	Pre	Post
PDE	0.39 (0.33)	0.23 (0.25)	0.47 (0.26)	0.14 (0.24)*
RQ	1.19 (0.20)	1.13 (0.20)	1.30 (0.33)	1.19 (0.12)
KQ	2.00 (0.51)	1.77 (0.52)	2.36 (1.21)	1.69 (0.53)*

Data for the postural disc effect (PDE) are expressed in centimeters of average deviation from the baseline position. Romberg Quotient (RQ) is the ratio sway path length with eyes open/eyes closed and the Kinetic Quotient (KQ) is the ratio sway path length during disc rotation/eyes open.

* $p < 0.05$ indicates a significant reduction compared to baseline assessment.

Table 2
Comparison of mean (SD) raw sway path data for COP in both groups at the pre- and post-intervention assessment.

	Group C		Group OKS	
	Pre	Post	Pre	Post
EO	41.73 (16.43)	44.77 (20.70)	34.48 (7.15)	35.14 (8.38)
EC	51.26 (27.49)	50.32 (23.90)	45.20 (16.10)	41.52 (10.38)
Disc	31.58 (24.37)	24.69 (24.97)	35.37 (32.28)	17.73 (19.54)*

EO = eyes open; EC = eyes closed. Data are presented in centimeters.

* $p < 0.05$ indicates a significant change compared to baseline assessment.

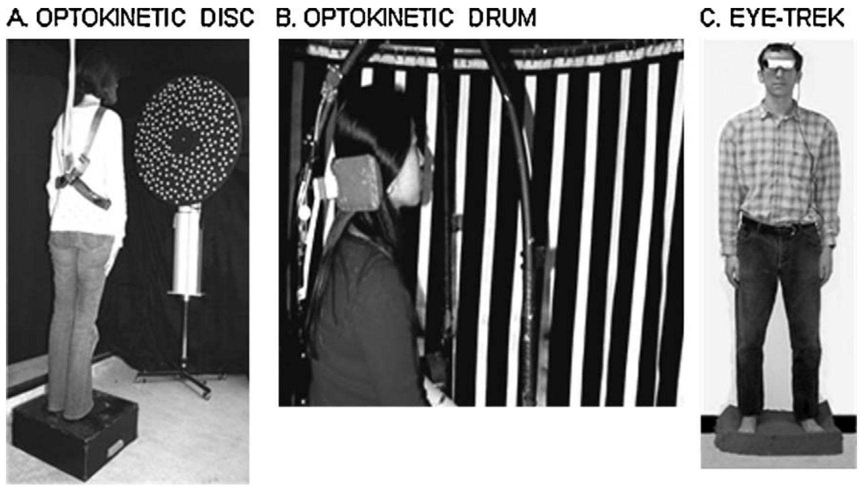

Fig. 2. Apparatus and sample exercises for the simulator-based intervention. (A) Optokinetic disc: a subject focuses on the black circle in the disc's centre while the disc rotates. (B) Optokinetic drum: the subject is seated in the stationary chair and asked to stare ahead while the drum rotates. (C) Eye-Trek: a subject stands on foam while viewing a visual motion scene with the Eye-Trek device. The velocities of motion employed are explained in Section 2.

4.1. Perceptual responses

The Rod and Frame [8] and Rod and Disc [9] tests assess static and dynamic aspects of perceptual preferences for spatial orientation, respectively. Baseline static and dynamic SVV direction and deviations were similar to previous reports for healthy subjects [4,9]. Inter-individual differences for spatial perception tasks are well documented within healthy individuals with some relying more on vision and others on vestibulo-proprioceptive cues [10]. These differences are reflected in our results' SD, which is similar to previous work where subjects were not pre-selected or separated into groups based on perceptual preference [4]. However, despite high intra-individual differences, the results are unambiguous.

The significant SVV deviation changes noted with exposure to repetitive vestibular and optokinetic stimuli indicate they are intervention dependent. Previous work, in patients with unilateral or bilateral uncompensated vestibular disorders, showing VV symptoms improve only when customized vestibular exercises are combined with OKS exposure supports this view [5].

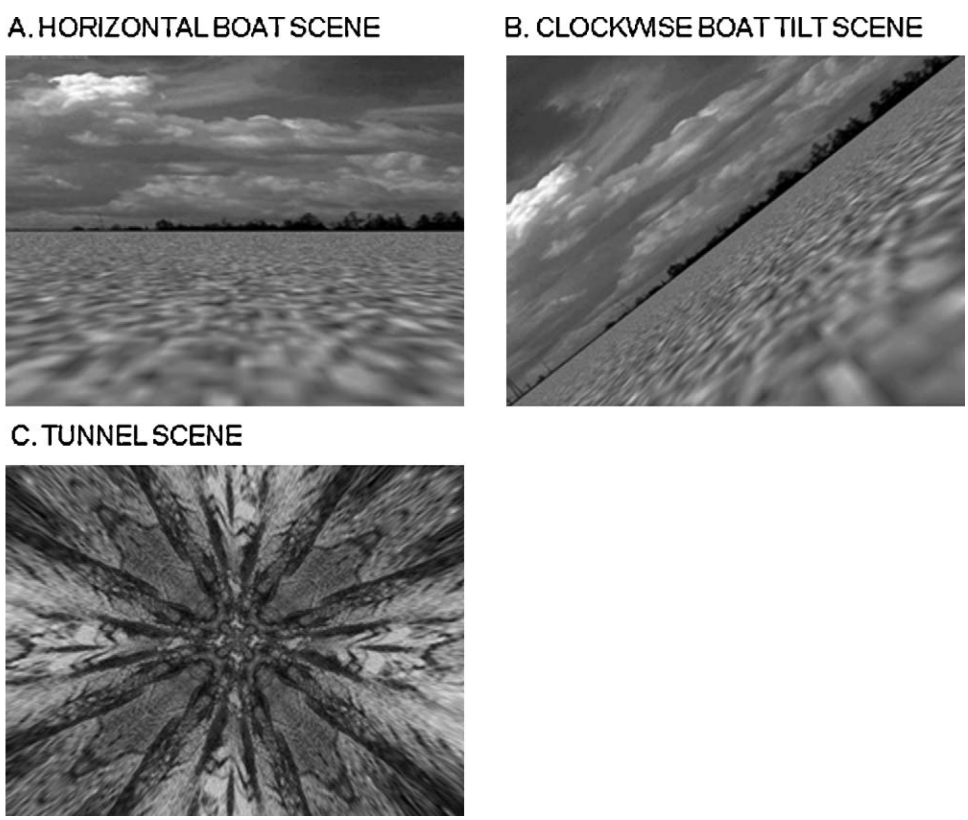

Fig. 3. Examples of the visual stimuli viewed with the Eye-Trek device as part of the simulator based intervention. (A and B) Images from the moving boat scene either in a horizontal position or tilted clockwise. (C) An image from the moving tunnel scene. The visual motion stimuli viewed by subjects were in color. Subjects were asked to focus on the centre of the moving scene while standing on a firm or compliant surface with or without simultaneously practicing sagittal or horizontal head movements.

The control group's non-significant static SVV tilt reduction has been demonstrated in previous work [11] and is believed to be due to a learning effect [12]. Furthermore, it is well known visual motion mediated postural effects decrease significantly or disappear completely with stimulus repetition [13] due to central suppression of visually evoked responses partly owing to sensory reweighing [13], cognitive-expectancy effects [14], and central visual motion adaptation (e.g. the mechanism underlying the waterfall illusion). The association between increased motion sickness and greater dynamic SVV tilt change is unsurprising as simulated motion and visual stimulation exposure is the established treatment method in the aerospace environment for susceptibility to disorientation and associated autonomic symptoms [15].

Adaptive changes in orientation perception occur during the microgravity conditions of parabolic flight where the magnitude of perceived body tilt and self-motion rapidly increase compared to normal gravity, suggesting increased visual dependency during the "0 polarity" phase [16]. The authors propose this results from a sensory re-weighting process whereby the perceptual system immediately recognizes the lack of visual input contradiction compared to temporarily absent otolithic and inaccurate somatosensory input and adapts accordingly [16]. Adaptation of specific vestibular parameters has been noted following OKS exposure including changes in vestibular ocular reflex gain in primates, healthy individuals, and chronic peripheral vestibular patients [17,18]. Post-rotational vestibular sensation duration also reduces in healthy subjects with exposure to repetitive, vestibular or optokinetic stimulation for five consecutive days [19]. However, this is the first study we are aware of showing changes in visual dependency magnitude following repetitive, progressive, daily exposure to combined vestibular and optokinetic stimuli. The aforementioned changes demonstrate neural adaptability in man.

Increased dynamic SVV tilt in patients with bilateral vestibular hypofunction [20] and the absent A effect when side lying in a patient with complete somatosensory deafferentation below the neck [21] identify vestibular information as the primary sensory input counteracting disorienting visual or somatosensory stimuli affecting verticality perception. An fMRI study involving small field OKS without additional vestibular stimulation confirms this view [22]. Activation was noted in cortical areas related to visual motion processing and eye movement control, and deactivation of parieto-insular vestibular cortices indicating a reciprocally inhibitory visual–vestibular interaction [22]. It is suggested this interaction is functionally important, and indicates a sensory-re-weighting process with greater weight given to the more reliable input thus suppressing the possible mismatch between contrasting sensory information [23]. We believe this sensory re-weighting process underlies the changes noted in visual dependency measures with dynamic SVV tilt. However, findings showing neuronal substrates in the cerebellum and brainstem are also involved in processing horizontal and vertical OKS [24,25] highlight that possible neural action sites for adaptive changes induced by visuo-vestibular conflict and OKS are numerous, due to the extensive convergence of these signals in the neuraxis.

4.2. Postural sway responses

OKS exposure increases postural sway in healthy adults, in the direction of motion as in our study [4,9,13]. The increased sway is thought to result from a misinterpretation that the visual flow is due to self instead of object motion [26]. Current findings show postural sway deviation and total sway path during disc rotation significantly decreased only for the OKS group. Non-significant reductions were also recorded for the control group. Previous studies show reduced postural sway, indicating adaptation to the visually evoked response, with subsequent trials [13,27]. These studies though were completed in a single session as opposed to our study where the control group attended on two separate occasions and completed one trial for each postural task. Control group results may be explained by high level processes including expectation which can reduce the threshold for perceiving motion [28]. Postural re-adjustments reduce for most subjects with prior knowledge of the upcoming OKS characteristics, since this information helps clarify whether the upcoming stimulus results from self or object motion [14]. However, the OKS group demonstrated further reductions for postural sway deviation and total sway path during disc rotation compared to the control group. As with perceptual responses, this additional improvement is interpreted as an adaptive change induced by OKS exposure.

Recurring exposure to conflicting visual input, as in our study, is believed to promote reduced visual reliance and foster a more effective use of vestibulo-proprioceptive cues for postural stability [29] through sensory re-weighting [27]. The mechanisms mediating sensory re-weighting in postural control, however, remain poorly understood [27].

The Kinetic Quotient decreased significantly for the OKS group but the Romberg Quotient showed no change, further supporting an intervention specific component to our findings. The Romberg Quotient relies on accurate use of vestibulo-proprioceptive cues. Furthermore, exposure to conflicting visual input is unlike absent vision which was not targeted in the current intervention. Therefore, no significant change is expected. Moreover, the average Romberg Quotient was smaller than previously reported for healthy subjects [4], limiting the available scope for change. Healthy subjects who exercise more than 3 h weekly (similar to our mean) sway significantly less during EO, but not EC stance [30]. However, weekly exercise did not affect the outcome of our study.

4.3. Clinical implications

Long-term static and dynamic SVV perception impairments have been noted in patients with peripheral vestibular loss indicating either asymmetrical processing of visual information or visual dependency [4,31]. Some researchers [31] believe these are permanent impairments, but our results in healthy subjects dispute this hypothesis. Current results suggest short-term repeated exposure to visuo-vestibular exercises induces plastic, adaptive changes which decrease (improve) the magnitude of visual dependency and has important implications for its treatment in individuals with/without vestibular dysfunction (e.g. older adult fallers [32], migraineurs [33], anxiety disorder [34]).

In patients with peripheral vestibular disorders, previous work incorporating OKS exposure included twice weekly sessions for eight weeks [5], which is impractical. Corna et al. [35] compared supervised exposure to either support surface translations or Cawthorne–Cooksey exercises for five consecutive days in a similar patient cohort who tolerated treatment. Although, we initially believed daily OKS exposure would be intolerable, current results in healthy subjects disprove this notion. These findings though cannot be extrapolated to a symptomatic patient population. Therefore, we are investigating whether patients with peripheral vestibular disorders (including migraine associated dizziness) can tolerate short-term graded exposure to vestibular exercises and OKS, its impact on visual dependency and rehabilitation outcome.

It is important to highlight that the current study is not a clinical trial involving patients and there are no treatment outcomes or symptoms. Therapist attention would be an unlikely explanation for the OKS group's results as in the aforementioned study by Pavlou et al. [5] attention was equal between groups indicating a more specific treatment effect on VV outcome.

5. Conclusion

Short-term repetitive, graded exposure to visuo-vestibular exercises induces plastic, adaptive changes which significantly reduce both perceptual and postural visual dependency measures only in subjects receiving the intervention. These findings have important implications for visual dependency treatment in patients with VV and balance disorders. However, patient tolerance, optimal treatment duration, and long-term benefit remain to be determined.

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Conflict of interest statement

The authors do not have any financial or personal relationships with other people or organizations that could inappropriately influence their work.

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